ENHANCED BEARING RELIABILITY THROUGH IMPROVED MOUNTING, SEALING AND MAINTENANCE

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SUMMARY

Anti-friction bearings (AFB) are found throughout all industrial facilities. AFB are critical to the operation of all rotating equipment including: electric motors, gear reducers, conveyors, fans and pumps. Mounted bearings describe a class of AFB that are contained in a self-supporting housing with a method of attaching the bearing to a rotating shaft. This paper will discuss the different types of anti-friction bearings and their application with specific emphasis on mounted bearings. Key topics of discussion include bearing types and materials, bearing selection, bearing load and life calculations, and the challenges encountered when handling large bore bearings. Methods of attaching bearings to shafts will be discussed as well as best maintenance practices for bearing storage, mounting and removal. Lubrication and bearing sealing options and their impact on reliability will be reviewed. An introduction to bearing failure analysis and how to use failure data to improve bearing reliability will also be presented. Examples of bearing failures will be reviewed to demonstrate the processes and the solutions for each case will be presented

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INTRODUCTION

Man has long developed methods to overcome the force that resists relative motion between two bodies in contact. Early methods to overcome this force, otherwise known has friction, were simple logs placed under a large stone to help move it across the ground. This early use of bearings over 6,000 years ago evolved over the millennia to the engineered, precision made bearings that we know today that are capable of operating at very high speeds and under extreme loads.

Modern bearings allow the relatively free (low friction) rotation of machine components while supporting the weight of the machine. Additionally, bearings may serve the purpose of maintaining the location of machine components relative to on another. Bearings in electric motors support the weight of the rotor, allow it to freely rotate, and also maintain both the axial and radial position of the rotor inside the motor stator.

Depending on the application, bearings can be subject to forces in the axial direction, radial direction or a combination of the two (figure 1.). Radial loads are forces acting on the bearing at right angles to the centerline of the shaft, while axial or thrust loads are forces applied in parallel to or in line with the shaft. As an example, the weight of an electric motor rotor and the magnetic forces inside the motor are a predominantly radial load for bearings. A centrifugal pump or fan, on the other hand, may be subject to significant axial (thrust) loads because of the nature of the work that the impeller must perform on the process fluid.

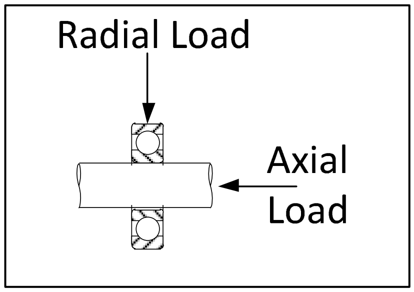


Figure 1. Radial and Axial Bearing Loads

The selection of the correct bearing for a particular application depends heavily on the type of load that the bearing must carry (axial and/or radial) as well as the speed that the supported load operates at. The wide range of industrial applications and environments has led to numerous bearing designs that can fit most application requirements.

This focus of this paper is mounted Anti Friction Bearings that are typically found in mining and industrial applications. A mounted bearing is a bearing that is supplied with a (1) bearing; (2) housing; (3) method to attach to shaft; and (4) a seal to protect the bearing from contamination. An un-mounted bearing would be supplied without a housing and mounting method and relies on the design features of the machine to provide an enclosure, attachment to shaft and sealing.

This paper will discuss the primary bearing types that are found in industry, the mounting methods, lubrication and maintenance of mounted bearings.

TYPES OF MOUNTED ANTI-FRICTION BEARINGS

Anti-friction (AF) bearings refer to a class of bearings that utilize rolling elements between two raceways to reduce the rotating friction of a shaft. Typical components of an AF bearing are the (1) Inner race; (2) outer race; (3) rolling elements; (4) cage.

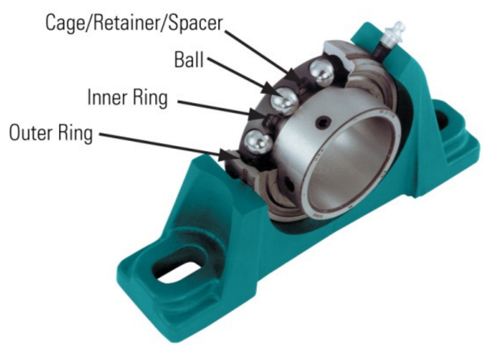


Figure 2. Bearing Parts

The inner and outer race of the bearing transmit the load from that shaft or bearing housing to the rolling elements as well as provide a track for the rolling elements to run in. The cage ensures uniform spacing of the rolling elements and prevents them from contacting one another.

Anti-friction bearings can be broken into two broad categories based on the geometry of the rotating element. A "ball" bearing refers to a bearing with a rolling element that is round and allow for a single point of contact between the inner and outer raceways. A "roller" bearing is a bearing with a larger contact area. A roller bearing can be made in several geometries including cylindrical, needle, tapered, or spherical.

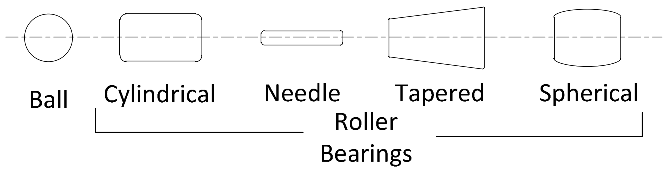


Figure 3. Bearing Rolling Element Geometry

A ball bearing will make contact with the bearing races in a relatively small area or point, which allows the bearing to rotate with little effort. This lower friction of the ball bearing generates less heat and allows them to operate at a high speeds. Because the contact area is so small, a ball bearing is limited on the load that it can carry. A roller bearing with a large contact area can accommodate a much higher load, but because of the increased contact area it will tend to run hotter than a ball bearing which will limit that speed that it can operate.

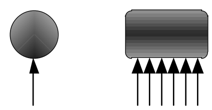


Figure 3. Bearing Contact Area

The choice of the type of rolling element in a bearing is predominantly determined by the axial and radial loads that the bearing must support as well as the operating speed of the bearing. In the next few sections is a description of the different type of mounted bearings and their load carrying characteristics.

Deep Groove Ball Bearing

The deep groove ball bearing is probably one of the most common bearings in industry. The rolling elements (balls) of this bearing ride in a grooved inner and outer rings that allow this style bearing to carry a combination of radial loads and/or axial loads. Because ball bearings have a single contact point, they are also suitable for high speed operation.

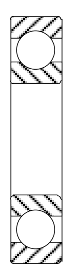


Figure 4. Ball Bearing

Spherical Roller Bearing

Spherical roller bearings are designed for moderate to heavy loading in both the axial and radial directions. The bearings consist of two rows of symmetrical barrel shaped rollers that rotate between an inner race and a spherical outer raceway. This outer raceway geometry allows the inner ring and rollers to align freely and account for any misalignment or shaft deflection.

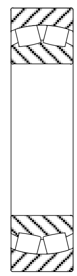


Figure 9. Spherical Roller Bearings

When subjected to axial loads, careful attention must be made to the ratio of the axial to radial load as well as the speed of the bearing to prevent excessive bearing wear. A general rule of thumb is one pound of radial load is required for one pound of axial load. The spherical roller bearing also has a minimum load requirement that is typically between 0.067% and 0.08% of the dynamic capacity of the bearing to prevent the rollers from skidding.

Tapered Roller Bearings

Tapered Roller bearings are used to accommodate both thrust and radial loads. If they are of a single row design, they can handle thrust in one direction only. The tapered roller bearing is often used in sets or in a duplex configuration that utilizes two bearings that face in opposite directions to accommodate thrust in two directions.

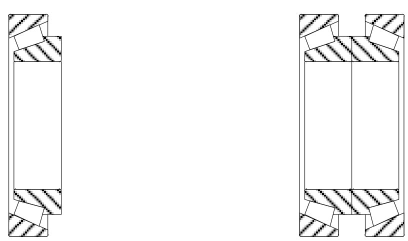


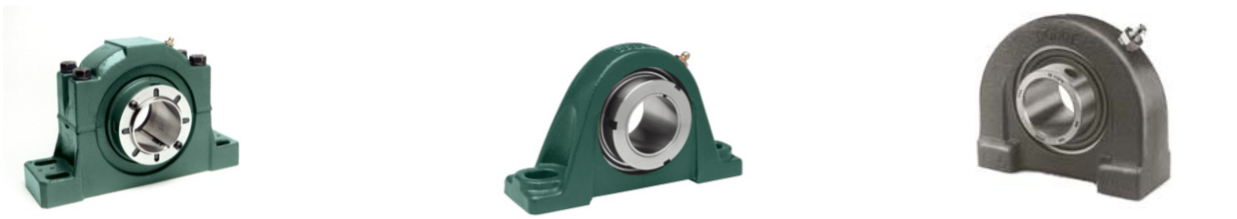
Figure 10. Tapered Roller Bearings

MOUNTED BEARING HOUSINGS

As mentioned early, a mounted bearing refers to a style of bearing that is self-contained in a housing. The bearing housing is designed to support the bearing, connect it to the machine structure, protect internal components from damage, and transmit radial and thrust loads from the rotating shaft to the machine structure. Housings help with the dissipation of heat from the bearing, also provide for the lubrication of the bearing and allowing for bearing shaft alignment.

Pillow Block Housing

The pillow block is the most common housing used with mounted bearings. The pillow block housing encompasses a large range of bore sizes and is easily adaptable to most applications. Two and four bolt patterns are typically used to fasten the housing to the machine structure. The pillow blocks can be a solid designed or a split housing. The split pillow block housing is common on larger bore bearings as it facilitates installation and allows the bearing to be replaced without removing the entire pillow block from the structure. The pillow block is also available in a compact version with bolt holes tapped in the bottom of the housing for securing to the machine structure.



Four Bolt Split Pillow Block   Two Bolt Enclosed Pillow Block   Pillow Block w/ Tapped Base

Figure 11. Pillow Block Housings

Flange Housing

The flange housing is designed to mount flush against a mounting structure and allows for assembly with mounting bolts in the same direction as the shaft. The flange housing is available with different bolt configurations as well as a piloted flange. The piloted flange on the back of the housing is designed to counter sink into the machine frame for additional stability of precision locating of the bearing.

Figure 12. Flange Housings

Take-Up Housing

The take-up housing is designed to fit in a frame that allows positioning of the bearing. One common application that uses a take-up housing is for the tensioning of a conveyor belt.

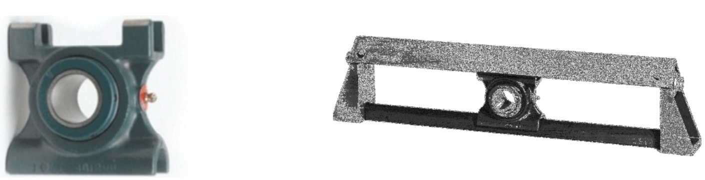


Figure 13. Take-up Bearing Housing and Takeup Frame

Housing Materials

Bearing housings are typically either cast or forged using materials suitable to withstand the stresses and environment conditions for a given bearing design and application. Typically, most housing are made from cast iron, but cast steel and ductile iron are often used when a stronger housing is needed or the housing is installed in extreme cold temperatures.

Cast iron housings are the typical housings for most general purpose applications. Cast iron is the lowest cost and is easily machined and adapted. The cast iron housing can handle light to fairly heavy loads in a wide temperature range. Common tensile strength for cast iron housings is in the 20,000 to 30,000 psi range.

Cast steel and ductile iron are ideal for rugged, heavy duty applications with high shock loads or extreme cold temperatures. Tensile strength for these housings is in the 65,000 to 100,000 psi range. Cast steel and ductile iron may not be as readily available as cast iron housings and generally cost more.

Polymer and stainless steel housing are also common in applications that are exposed to caustic cleaning solutions or were cleanliness is important.

SHAFT ATTACHMENT

Mounted bearings are designed to be slipped over a shaft and then secured to the shaft with a locking mechanism. There are several methods utilized to secure a mounted bearing to a shaft, with the simplest being the set screw.

Set Screw Mounting

A set screw mounting is a very simple method that incorporates setscrews threaded into an extension of the inner race, or a separate spring lock collar that slides over the extended inner race. The threaded holes in this lock collar match holes that are in the inner race. The spring lock collar has an advantage of not deforming the inner race compared to a bearing that has set screws that are threaded directly into the inner race. Typically, the spring lock collar is used on most spherical mounted bearings as well as larger ball bearings.

Setscrew bearings are economical and easy to install, however, they are limited in speed due to the eccentric nature of the mounting arrangement. When tightened, the set screws will dig into the shaft, pushing it to the opposite side of the inner race. This results in the shaft not running in the center of the bearing and makes the performance of the bearing reliant on the tolerance of the shaft diameter. The set screw bearing does have an advantage over other mounting methods when subjected to thrust loads. Because the set screws protrude into the shaft they will have to "plow" through the shaft material to move axially.

Concentric Locking Collar

A concentric locking collar uses a split collar with one or more clamping screws. This clamping collar fits over an extended inner ring which has radial slots to allow the compression of the inner ring extension. When the bearing is in the proper position on the shaft, the lock collar cap screws are tightened to close the collar, compressing the inner ring and fixing the bearing to the shaft. One advantage to a concentric locking collar over the set screw collar is the 360^0 contact of the inner ring with the shaft which results in the bearing centered on the shaft. This mounting also does not mar the shaft, but is limited in axial thrust holding capability.

Eccentric Locking Collar

The eccentric locking mechanism uses a cam design to create a wedge effect and secure the inner race to the shaft. The cam action is created by the eccentricity of the inside diameter of the locking collar in relation to the engaging extension of the inner ring of the bearing. Typically, this collar secures the bearing in position with ¼ turn. A setscrew in the lock collar that contacts the shaft prevents the collar from coming loose. The eccentric locking collar has similar characteristics as the set screw bearing with additional limitations on reversing applications.

Set Screw Eccentric Collar Concentric Collar

Figure 14. Set Screw and Collar Mounts

Tapered Adapter Mount

A tapered adapter is a type of mounting that utilizes a bearing with a tapered bore of the inner race. The taper in the bearing inner bore matches the taper of a split adapter sleeve that slides between the bearing bore and the shaft. During mounting, the bearing inner race is pushed up the tapered "wedge" of the inner sleeve, with the "wedge" creating the locking force that holds the bearing to the shaft. The tapered adapter mounting has the advantage of providing a concentric 360^0 locking that centers the bearing on the shaft as well as greatly reduces movement between the bearing and shaft that can cause fretting corrosion.

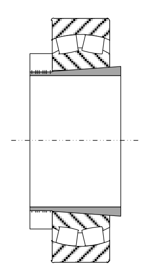


Figure 15. Tapered Adapter Mount

BEARING SEALS

Bearing seals for mounted bearings come in a variety of arrangements that range from a simple clearance gap seal to a combination seal that may include several different types of seals. Seals provide the basic function of keeping contamination out of the bearing, as well as keeping the lubrication close to the bearing moving parts. In the case of a grease lubricated bearing, the seal may help form a grease "dam" that further protects the bearing from contamination.

Clearance Seals

A clearance seal consists of multiple stationary rings or washers of rigid material. This seal does not make contact with the rotating surface of the bearing, but runs very close to it. The absence of rubbing components allows for reduced operating temperature and higher operating speeds. A clearance seal is effective at blocking medium to larger contaminates, but in an environment that has finer dusts or liquid contamination may not protect the bearing.

Contact Seals

A contact seal typically incorporates a resilient flexible component that completely closes any path for contamination to enter the bearing. Because the flexible element has a lip that makes contact with the rotating components of the bearing, it is often called a "rubbing" or a "lip" seal. Contact seals can be arranged with single or multiple lips to improve the performance of the seal. Because the contact seal has components that are in relative motion and in contact, it will tend to generate heat at higher speeds. The contact seals also will wear and will need to be replaced periodically. Additionally, in an application where the environment is abrasive, contamination can combine with the grease and lip seal to damage a rotating shaft. Typically the contact seal is best suited for slow to moderate speeds in most any type of environment.

Labyrinth Seals

In contrast to a contact seal, the labyrinth seal protects the bearing without completely providing a closed path to contamination. The seal provides a series of passages with bends (maze) that the contamination must travel to before it reaches the bearing. Typically, in a grease lubricated bearing, the old grease purges through these passages when the bearing is re-lubricated, forming a dam that prevents contamination from entering the bearing. Because the labyrinth seal is a non-contact seal, it is suitable for high speeds that a contact seal. A typical labyrinth seal that is found on mounted spherical bearings is the LER type seal. The LER seal may be polymer or metalic construction (metalic allows higher operating temperatures) and usually consists of a seal that fits loosely on the shaft that engages with matching grooves in the bearing housing.

Combination Seals

A combination seal combines the sealing features of different type of seals into a single seal. The seal shown here combines a labyrinth LER seal with a contact lip seal that also acts as a flinger to throw contamination away from the seal when the shaft is turning. In this seal, contamination must pass under the lip and then through the labyrinth to reach the bearing. The addition of the LER also provides additional sealing should the contact seal become damaged or is worn. A common type of combination seal is the Taconite seal that was designed for the fine, abrasive dust of taconite mines. Different vendors will have their version of the Taconite seal, but the basis design of a Taconite seal consists of a labyrinth seal with an additional auxiliary rubbing seal and the provision for lubrication. The Taconite seal can contain an additional rubbing seal or flinger. Because of the external design of the Taconite seal, it increases the length though bore of the bearing assembly which reduces the misalignment capability of the bearing.

Shields or Flingers

A shield or flinger is used as a deflector to protect the primary seal from damage due to larger particles or sprays. The slinger is attached to the rotating portion of the bearing or shaft and is designed to fling material away from the bearing by using rotational centrifugal force.

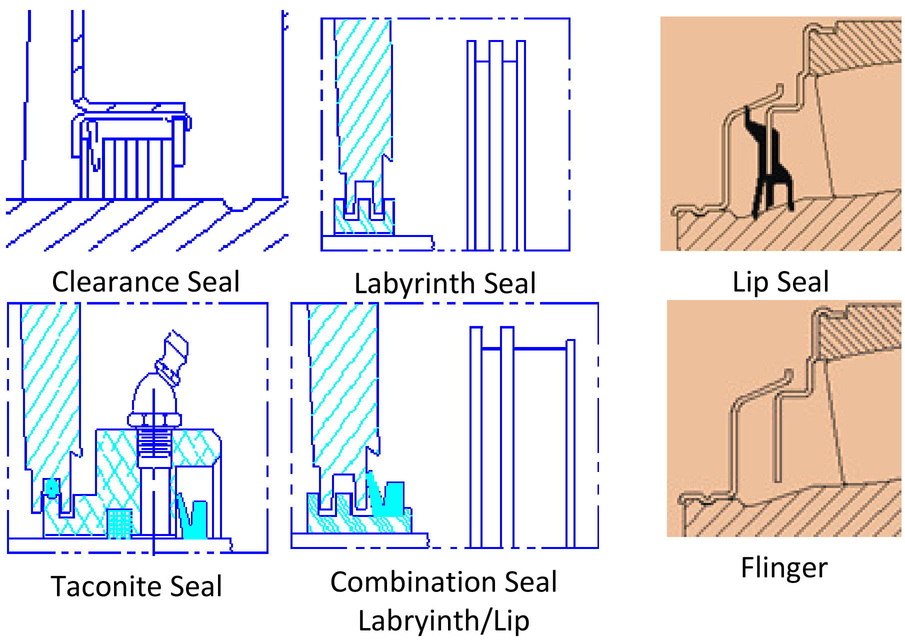


Figure 16. Typical Seal Arrangements

BEARING SELECTION

Selecting the correct mounted bearing for the application usually starts with an analysis of the loads and speeds that the bearing will be exposed to as well as the shaft diameter. For light to medium loads at moderate to high speeds, a ball bearing may be the proper bearing. For heavier loads and axial loads, the bearing may need to be a spherical or tapered roller bearing. Each bearing has a dynamic load capacity, C, that is determined by the bearing manufacturer. Knowing the bearing dynamic capacity, the speed of the shaft and the equivalent radial load that the bearing is carrying, the theoretical bearing life L_{10} can be calculated. The bearing L_{10} life is the life attained by 90 % of a statistically similar group of bearings operating under similar load and speed conditions. For users, the L_{10} life of a bearing is how long a bearing can be expected to last under ideal lubrication conditions. When a bearing has reached it's theoretical L_{10} life, the expected failure mode of the bearing would be a fatigue failure of the bearing load carry components (inner race, outer race or rolling elements). This failure mode typically manifests itself with material spalling from the raceways.

Often the initial selection of a bearing (size and type) is based on previous experience with the application as well as a general review of the shaft speed and loads. Once an initial selection has been made, there are a few steps to ensure the bearing will meet the requirements of the application.

Step 1. Determine bearing equivalent loads

Bearing load determines the amount of stress on the bearing and is directly related to it's life. Normally a bearing can be subjected to loads in radial and/or axial directions. These loads must be resolved into a single load known as the equivalent radial load (P).

When the load on a bearing is solely a radial load, the equivalent radial load (P) is equal to the actual load.

When a thrust load is applied along with a radial load they must both be converted into an equivalent radial load:

$$P = XF_R + YF_A$$

Where:
P = Equivalent radial load
F_R = Radial load
F_A = Thrust load
X = Radial load factor (from bearing manufacturer)
Y = Thrust load factor (from bearing manufacturer)

Step 2. Determine bearing L10 Life

Once the bearing equivalent load is known, the bearing L_{10} life in hours can be calculated for the chosen bearing using one of the below equations depending on the bearing being used:

Ball Bearing	Spherical Roller Bearing	Tapered Roller Bearing
$\left(\frac{Cr}{P}\right)^3 x\ 16{,}667/rpm$	$\left(\frac{Cr}{P}\right)^{10/3} x\ 16{,}667/rpm$	$\left(\frac{C90}{P}\right)^{10/3} x\ 1{,}500{,}000/rpm$

Where:
C_r = dynamic capacity for ball and spherical roller bearings
C90 = dynamic capacity for tapered roller bearings
P = equivalent radial load
rpm = speed of the rotating ring.

As mentioned above, the L10 life of a bearing is the theoretical life of a bearing in "ideal" conditions. Most bearings operate in less than ideal conditions and may be subject to number of factors that can shorten the life of a bearing. Because of this, when selecting a bearing it is important to specify a minimum L10 that will ensure the bearing will meet the users requirements. Normally, when the bearing L10 is greater than 100,000 hours, the fatigue life of the bearing is considered to be insignificant as the bearing will probably experience a different failure mode such as lubrication failure, contamination, etc.

Step 3. Check the bearing max speed

Most manufacturers will provide a catalog maximum speed for a particular bearing. The bearing itself may have mechanical limitations such as strength or seal noise that determine the maximum speed that it can safely operate at. The bearing also has thermal limitations that may limit the speed that the bearing can operate. Friction forces in the bearing generate heat, that can affect the life of a bearing. Bearings with plastic cages will have a thermal limiting speed because of the temperature limitation of the cage material.

Step 4. Choose the mounting method, seal configuration, housing

Once the suitable bearing has been chosen, the mounting method, seal and housing type will need to be selected.

BEARING STORAGE AND INSTALLATION

Bearing Storage

As with precision machine components, mounted bearings are sensitive to improper storage and handling. All bearings should be stored in a cool dry area. Often the manufacturer supplies a bearing in packaging designed to protect unused bearings from the effects of humidity, handling and exposure to contamination. Keep the bearings in their original packaging until ready for use. Mounted bearings usually come with a factory packed lubrication, oil, or rust preventative that also will protect the bearing. If the bearing does not have any factory lubricant, covering the bearing with an additional light coating of a rust preventative may extend the storage life of the bearing. When a bearing remains in storage for an extended period of time, the following precautions should be taken to extend shelf life:

- Coat the bearing and housing bore assembly with a corrosion inhibitor, lubricating oil, or grease.
- Apply a bead of #3 or #4 grease at the junctures of the seal, housing, and shaft.
- Seal all vents and other openings to the pillow block.
- Rotate the shaft a minimum of 10 – 20 revolutions every two to six months. This will re-coat the bearing surfaces and reduce corrosion.
- Bearings should then be packaged within plastic sheeting, but should not be completely sealed as this can trap humidity.
- Store the mounted bearings in a temperature controlled and dry area. The temperatures should not exceed 120º F maximum, -20º F minimum; the relative humidity should not exceed 60%.

- Inspect the stored bearings at regular intervals. Check for oxidized or hardened grease, brittle seals and corrosion in and around the bearing. The standard shelf-life for long-term bearing storage is approximately three to five years mostly because of the limited shelf-life of the factory lubricated bearing and nonmetallic component of the bearing (i.e., rubber contact seals.)

Bearing Installation

Most mounted bearings are slipped over the shaft and secured with one of the locking methods described earlier. The slip fit is necessary for an easy installation; however an undersized shaft can affect the performance of the mounted bearing with higher vibration and temperatures as well as a reducing the reliability of the locking device. Once a locking device is loose, it allows the shaft to rotate in the bore of the bearing damaging the bearing and the shaft.
This is why it is important to check the shaft tolerance regardless of the locking mechanism and ensure that it meets the bearing manufacturer's requirements. The shaft should be straight, free of burrs and nicks.

Most shafts are supported by two bearings, one fixed and the other floating. The floating bearing is allowed to move a small amount in the axial direction to allow for shaft expansion. The fixed bearing should be mounted first.

Set Screw and Lock Collar Bearings

Set screw and lock collar bearings are the easiest to install. First lubricate the shaft and bearing bore with a light oil to facilitate assembly, and then slip bearing into position. Determine final shaft position and tighten setscrews on the fixed bearing to their recommended torque. Rotate the shaft slowly under load, if possible, to properly center the rolling elements with respect to the raceways. Then tighten setscrews of the remaining bearing to the recommended torque.

Tapered Adapter Mount Bearings

Because tapered adapter mount bearings rely on the clamping force of the tapered sleeve and the inner bore of the bearing, proper mounting is a bit more complicated than a set screw or lock collar bearing. As the bearing inner race is pushed up the adapter wedge, the inner race actually expands to provide the locking force. If the inner race is not pushed far enough up the sleeve, the bearing will not have enough locking force and may come loose. If it is pushed up the sleeve too far, then the inner race may expand too far, taking out to much clearance between the inner and outer races and causing the bearing to run hot or actually crack the inner race of the bearing.

There are several methods that can be used with tapered adapter mount bearings ensure correct mounting. The goal of any method is to remove the requisite amount of clearance (clearance reduction) during mounting, ensuring that there is adequate locking force on the shaft. The basic method requires using feeler gauges to measure the "bench" clearance of an un-mounted bearing. Once the initial clearance is known, a final target clearance is determined by subtracting the "clearance reduction" from the initial clearance. The bearing is then mounted on the shaft, and the inner race is pushed up the adapter sleeve by turning a nut with a spanner or drift and hammer. As the nut is tightened, the clearance is checked with feeler gauges until the required amount of clearance is removed.

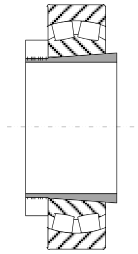


Figure 17. Tapered Mount Bearing

Figure 18. Checking Bench Clearance

In larger tapered adapter mount bearings, the force needed to move the bearing up the adapter sleeve can be excessive. Often a large sledge hammer and heavy spanner are needed to hammer the nut around. An alternative to this method is to use a special nut with an annular hydraulic piston that pushes the bearing inner race up the adapter sleeve using hydraulic pressure from a hand operated hydraulic pump.

Self Contained Mounted Bearings

Because of the complexity and uncertainty of the clearance reduction method of mounting bearings, manufacturers have developed bearings that are factory assembled into a single unit, complete with attachment locking device, seals and bearings. Often these bearings come from the manufacturer pre-lubricated. These cartridge style mounted bearings may be ball, tapered or spherical roller bearings with any of the mounting methods described above. If a cartridge bearing use a tapered adapter sleeve, the clearance cannot be measured with feeler gauges because of the bearing seals. For these style bearings, manufacturers have already determined the initial clearance of the bearing and will require turning the mount nut a requisite number of turns to mount the bearing.

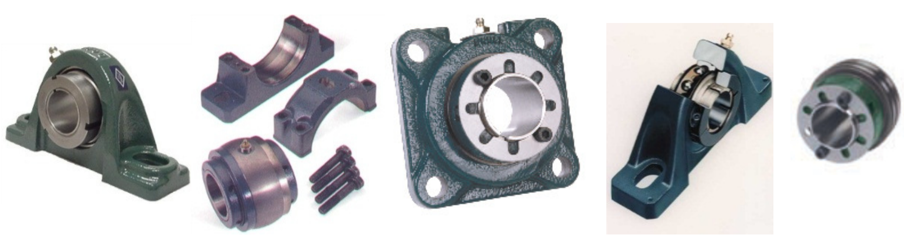


Figure 19. Self Contained Bearings

For the taper sleeve bearing this mounting method has significant advantage over using feeler gauges and can significantly reduce the time needed to mount the bearing as well as improve the reliability of the mount. Additionally, the cartridge bearing comes to the jobsite with a lot less parts than the traditional bearing and because they are pre-sealed and pre-lubricated the cartridge bearing keeps the bearing clean during installation

Figure 20. Comparison of Self Contained SAF to standard SAF

BEARING LUBRICATION

Lubrication is one of the most important aspects of a bearing service life and performance. A bearing lubricant has several functions that are discussed in the following paragraphs.

The primary purpose of lubrication for anti-friction bearings is to reduce the friction between the contact areas within a bearing. While the bearing surfaces are designed to be low friction, there are still enough irregularities on the contact surfaces so that they have a frictional force. The lubricant forms a film between the contact surfaces irregularities.

The second function of lubrication is to reduce wear of the moving surfaces in the bearing. As the irregularities of the moving surfaces come under load, the inherent strength of one surface will overcome the strength of the other surface and shear away as small particles. Not only does this wear result in the loss of the softer material, it also introduces particle contamination into the lubricant. When lubricant is present as a layer between the two surfaces, it reduces the wear.

The third function of lubrication is to carry away heat generated by the friction and wear activity that occurs in the bearing. The lubricating fluid between the two surfaces provides a medium for carrying away the heat from the bearing materials to an area where it can be dissipated.

A fourth important function of lubrication is to protect the bearing from contamination. Many bearings operate in environments that have ambient conditions that are a detriment to the life of a bearing. Moisture, abrasive dust, corrosive liquids and vapors will all attack the polished surfaces of an anti-friction bearing. Lubrication acts as a barrier that protects the contact surfaces of the bearing.

Lubrication of mounted anti-friction bearings is either accomplished by using oil or grease, with the majority (about 95%) using grease. Because the majority of bearings are grease lubricated, we will not discuss oil lubrication in detail in this paper.

Grease Lubrication

Greases used in bearing lubrication consist of two major components (1) the oil that provides the lubrication and (2) the thickener that holds or suspends the oil in the grease. Grease will also have a variety of additives such as rust inhibitors, anti-oxidants, wear inhibitors.

The oils that are used in greases typically fall into four categories in order of significance (1) mineral; (2) Synthetic; (3) Food grade; (4) exotic (silicone). Lithium, lithium complex and polyuria are three common thickeners that are found in greases.

The oil in the grease and the thickener work together to provide a lubrication "system" for the bearing. The thickener acts as a sponge to hold the oil in the grease. Then as the grease comes under load in the bearing, the oil is squeezed out of the thickener to provide the lubrication film for the bearing.

When selecting a grease, there are five key factors that need to be evaluated for the application:

1. Consistency of the Grease (NLGI #)
2. Viscosity of the Oil Within the Grease (cst)
3. Soap Base Properties (Lithium, Aluminum, Polyurea, etc.)
4. Load Carrying Properties (EP additives)
5. Operating Temperature Range

Grease Consistency

The consistency of a grease is controlled by the thickener concentration, thickener type, and viscosity of the base oil. The consistency of a grease is it's resistance to deformation caused by a force. Grease that is to stiff may not feed into all areas of a bearing that need lubrication. A grease that is to thin may leak out, or in the case of higher speed applications, leak back into the ball path, creating churning and excessive heat. The rating of grease consistency is known as the NLGI number. The most common NLGI number found in greases is #2. A higher NLGI number indicates thicker grease and a lower number indicates thinner grease. The selection of NLGI number is based on the operating temperature of the bearing and the speed factor (DN) of the bearing where DN is the product of the bearing bore and the RPM of the bearing. The below table can be used to determine the recommended NLGI number for a particular bearing

Operating Temperature	DN (Speed Factor)	NLGI #	
-30 to 100°F	0 - 75,000 75,00 - 150,000 150,000 - 300,000	1 2 2	***VERY SOFT***
0 to 150°F	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 2 3	↓
100 to 275°F	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 3 3	***HARD***

Table 1. Grease Consistency Selection

Oil Viscosity

The viscosity of oil is a measurement of the fluid's resistance to flow. Effectively this can be thought of as the "thickness" of the oil. The viscosity of a lubricant is normally measured at 40^0 C. When the temperature of oil increases, it becomes thinner or at a higher temperature the *operating viscosity* of the oil is lowered. The operating viscosity of an oil is critical to the effectiveness of the lubrication. A grease should be chosen that has an operating viscosity that is greater than the required or *Rated Viscosity* for a particular bearing. The Rated Viscosity for a bearing is a function of the mean bearing diameter (dm=(bearing bore + bearing O.D) / 2) and the operating temperature of a bearing.

Several bearing manufactures including Baldor-Dodge, SKF and FAG have useful online tools that will help a user determine the correct lubrication for a particular application.

Thickener Properties

Selection of the thickener is usually determined by the operating environment. Most thickeners are metallic soaps that form a fiber structure that gives the grease it's semi-solid body. The chart below shows the most common soap based thickeners plus one non-soap based thickener, Polyurea, which has become popular with electric motor manufacturers. Note that this chart is general comparison of thickener types and specific grease manufacturers can adjust properties in their specific greases.

Grease Type	Temperature Range (F)	Water Resistance	Corrosion Resistance	Load Carrying Capacity	Remarks
Lithium	-30 to 265	Very Good	Good	Good	Multipurpose grease, emulsifies with water
Lithium Complex	-30 to 300	Good	Moderate	Good	Multipurpose grease, emulsifies with water
Polyurea	-15 to 320	Very Good	Moderate	Good	For higher temp at medium speeds
Calcium	-20 to 120	Very Good	Good	Moderate	Good sealing against water. Temp limited
Calcium Complex	-20 to 285	Good	Good	Good	Multipurpose Grease, may harden, poor pumpability
Barium Complex	-20 to 285	Good	Very Good	Good	Multipurpose grease. Good in vacuum env. expensive
ALComplex	-20 to 320	Very Good	Very Good	Moderate	Multipurpose grease
Sodium	-20 to 210	Poor	Very Good	Good	Emulsifies with water, may solidify

Table 2. Grease Thickener Properties

Because there are so many types of grease thickeners available, invariably situations occur in plants where maintenance staffs are faced with the question of mixing greases, either intentionally or accidently. If possible, the grease manufacturer should be contacted to see if they have actual compatibility test data for the two greases.

Load Carrying Properties

After considering the NLGI #, viscosity and thickener of the grease, the need for additives that improve the strength of the grease under Extreme Pressures (EP) needs to be evaluated. Typically these EP additives work to improve the strength of the oil film and prevent it from being torn apart by high loads such as vibration and shock. One downside to EP additives is that they can cause a bearing to run hotter than a grease without EP additives. This is important for higher speed applications such as fans and motors as this heat can lead to early failure of the lubrication.

Operating Temperature

The factor to consider is the operating temperature of the application. Operating temperature is important not only from the effects of a high temperature on the grease, but low temperature can also be a concern. A grease that becomes very stiff at low temperatures can cause a particular application to be difficult to start in cold weather. The type and amount of thickener used and the base oil type (mineral or synthetic) determine the upper and lower operating temperature limits of a particular grease. As a rule of thumb, mineral oil based complex greases are suitable for temperature ranges of -22^{0}F to $+200^{0}$F. Synthetic oil based greases can give better performance on both the low and high end with typical temperature ranges of -100^{0}F to $+350^{0}$F.

BEARING FAILURE ANALYSIS

Few mounted bearings reach their theoretical L10 life, with some failures occurring at a fraction of what the mechanical life of the bearing should give. Often premature failure of bearings is accepted as a normal occurrence and little work is done to determine the root cause of the failure. The below chart shows over 15 years of data collected by a mounted bearing manufacture from analysis of failed bearings. From this chart, one can see that 55% of the bearings analyzed had lubrication related failure.

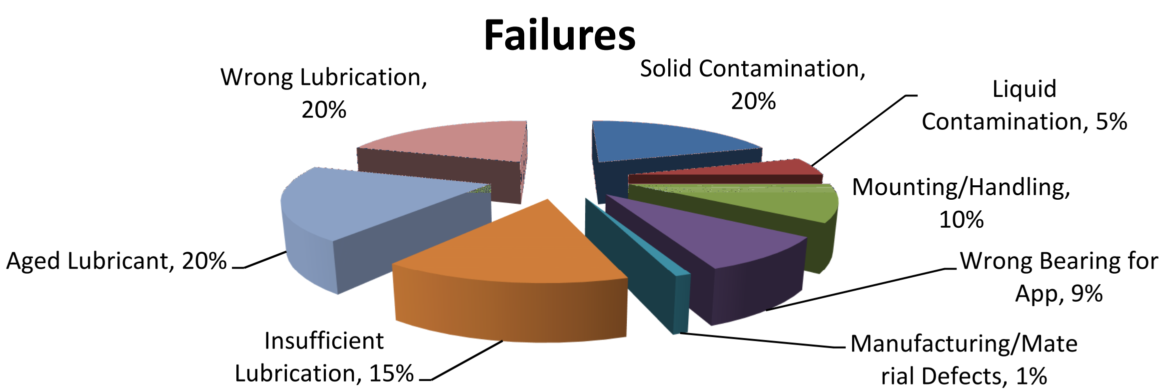


Chart 2. Bearing Failures

Taking the time to analyze a faile[d bearing can provide info]rmation that can help improve the life and reliability of the bearing. Sometimes the bearing suffers a catastrophic failure, but often it exhibits signs of impending failure such as increased vibration, temperature and noise that are indication of pending failure. If possible, removing the bearing from service before it fails catastrophically can provide good forensic data that point to a probable cause of the failure. A complete discussion of bearing failure analysis is beyond the scope of this paper, but below is an example of the value that taking the time to properly analyze bearing failures.

This customer removed this spherical mounted bearing from a conveyor after approximately 6 months of service because of excessive noise.

Figure 21. Failed Inner and Outer Bearing Races

Examination of the inner and outer races showed several problems that included high vibration (washboard pattern on outer race) and excessive wear caused by grease contamination. In this example, recommendations were made to upgrade the conveyor structure to limit vibration, improved bearing sealing from a standard LER seal to a combination LER with additional lip seal and ensure that grease used was an EP rated grease.

Because of the extreme conditions that this bearing operates in, an additional improvement could be converting the bearing from a standard adapter mount bearing to a sealed cartridge bearing that would come pre-assembled and pre-lubricated, eliminating contamination from getting into the bearing during installation.

CONCLUSION

Mounted bearings are available in a wide range of types, styles and sizes to fit most mining and industrial applications. The proper selection of the mounted bearing includes evaluating the key features of bearings and how they fit the specific needs of the application:

1. Bearing type (ball or roller) is determined by the load (axial and radial) and the speed of the application
2. The housing type determines how the bearing is mounted to the machine. A wide range of housing styles (flange, pillow block, take-up) are available as well as materials. The choice of housing material often is determined by the operating environment.
3. The method of attaching the bearing to the shaft is important both from an ease of installation as well as the reliability of the bearing. The simplest set screw mount bearing is easy to install, but results in an eccentric fit on the shaft that limits the speed of the bearing. A locking collar design bearing allows higher speed operating because of the concentric mounting, but will not handle the same thrust load that a set screw can. A tapered adapter sleeve has the advantage of the concentric mounting with a higher thrust load capability, but also can be more complicated to install.
4. One of the most important components of the bearing is the seal. There are several types of seals available that can be used singularly or combined to improve the performance of

each other. The basic labyrinth (LER) seal can be combined with a lip seal, or multiple lip seals can be combined with an external flinger that protects the rubber lip seal.

Once the bearing has been selected, the proper choice of lubrication is important to the life of the bearing. There is a variety of grease choices available with different lubricating oils, viscosities, consistency, thickeners and additives that can affect the bearing in a particular application.

Manufactures are always working to improve the mounted bearings with new designs of sealing and mounting systems. By building these improvements into integral cartridge bearings, users now have the option of choosing a bearing system that is easy to install, pre-lubricated with the

REFERENCES

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